Experimentation, data collection, modeling and simulation of pedestrian dynamics*

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Forschungszentrum Jülich

- Multidisciplinary research center
  - Health
  - Energy
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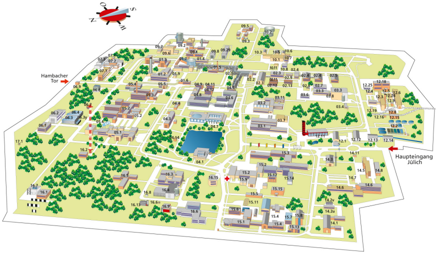

- Approx. 5000 employees

- Jülich Supercomputing Centre – Division Civil Safety and Traffic
  - Experimentation of pedestrian dynamics
  - Fire and evacuation simulation
  - Safety of large-scale events
  - Collaboration with Wuppertal University

Motivations

- Nowadays more than half of mankind lives in cities
- Dense crowds are frequent in train stations, fairs, city centers or during large-scale events (sport, spectacle, concert, demonstration. . .)
- Knowledge of pedestrian dynamics is important for the design and optimization of facilities with respect to safety or level of service
- Experimentation, data collection, modeling and simulation of pedestrian dynamics are necessary

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Experiments in laboratory conditions

Date	Place	Institution	# pers.	# run	Geometry
⋮					
2005	Germany	FZ Jülich	60	18	Bottleneck
2006	Germany	FZ Jülich	200	99	Corridor, bottleneck
2006	Netherlands	TUDeft	136	42	Boarding
2008	China	Hong-Kong Uni.	180	10	Intersection
2008	India	IIT Kampur	64	6	Ring
2008	Germany	Wuppertal Uni.	50	14	Ring
2009	France	INRIA Rennes	119	11	Ring
2009	Germany	Hermes project[1]	350	170	Diverse geometries
2013	Germany	BaSiGo project[2]	926	190	Congested situations
2013	Japan	Tokyo Uni.	28	260	Corridor, junction
⋮					

[1] In collaboration with FZ Jülich and Wuppertal University, see S. Holl and A. Seyfried. InSiDE 7(1):60 2009

[2] `www.basigo.de`

BaSiGo project

- BMBF-funded German project[3]

  $\rightarrow$ Developing safety and security modules for major events

- Approx. 1 000 participants over 4 days in a 10 000 m^2 hall (Düsseldorf Messe)

  30 experiments (corridor, bottleneck, intersection...) with a total of 190 runs

- Analysis of dense crowds with density higher than 6 ped/m^2

- High accuracy recording of the trajectories with special video technology based on a grid of 26 industrial cameras

[3] `www.basigo.de`

BaSiGo project

Photo: Michel Strunz

BaSiGo project

Photo: Michel Strunz

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BaSiGo project

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BaSiGo project

Photo: Michel Strunz

BaSiGo project

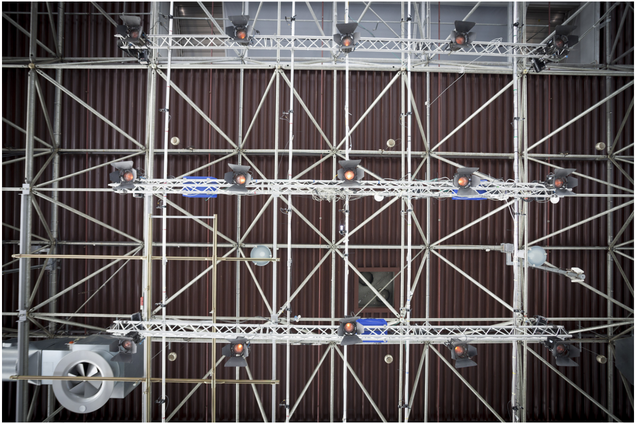


Photo: Michel Strunz

BaSiGo project

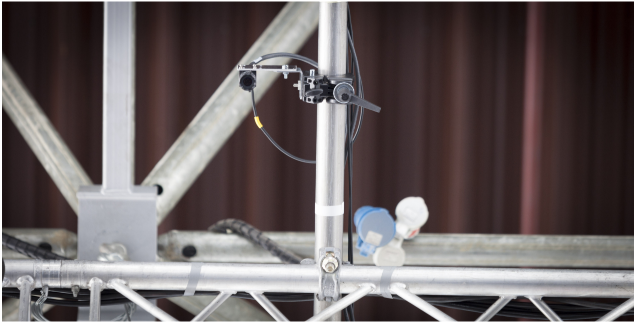


Photo: Michel Strunz

Collection of trajectories

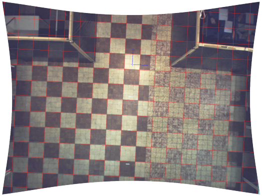
- PeTrack[4] is a software specially created to collect pedestrian trajectories from ordinary video recordings
- Procedure with 3 phases
  - **Calibration** : Correction of the distortion effects and optimization of camera position and settings
  - **Recognition** : Identification of the pedestrians in each picture of the videos
  - **Tracking** : Following of each pedestrian to obtain the trajectories

[4] `ped.fz-juelich.de/petrack/`

Calibration

- Optimization according to placement of the camera (height above the floor. . .) and its own properties (focal length. . .)
- Pedestrians positions in 3D are non-orthogonally projected onto a 2D plane

  $\rightarrow$ Correction of the distortion effect



Recognition

- Finding the pedestrians in the video recordings
  → For example by locating their heads
- Two methods for pedestrians with and without marker
  - Analysis of pixels brightness for markers equipped pedestrians
  - Use of distances from the top when no marker (the distances are calculated by using triangulation with the images of two synchronous cameras)
- Exist many other techniques, based on 3D, infrared, thermal or laser cameras or by color or movements detection[5]

[5] see M. Boltes. Automatische Erfassung präziser Trajektorien in Personenströmen hoher Dichte. PhD thesis, Universität zu Köln, 2014

Tracking

- Pedestrian trajectories determinate by linking the position of each pedestrian to the closest position at the next time step
- Confusions that can be obtained when two pedestrians are sufficiently close to be permuted are avoided by using high enough frames and predicting the position

Petrack results[6]

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[6] `ped.fz-juelich.de/petrack/`

Main variables

- Microscopic variables (pedestrian)
  - Pedestrian position, speed, acceleration rate, spacing distance, spacing time, time-to-collision...

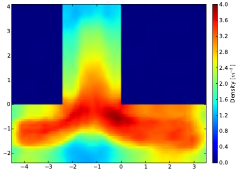
  $\rightarrow$ Lagrangian coordinates (n, t) with n pedestrian id. and t the time

- Macroscopic variables (pedestrian streams)
  - Density, mean speed, flow...

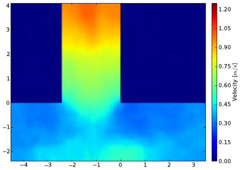
  $\rightarrow$ Eulerian coordinates (x, t) with x the position and t the time

Macroscopic variables

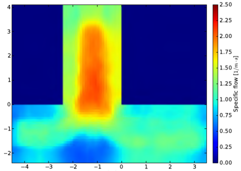
- Extracted from fluid dynamics (many definitions exist)
  - Continuous definitions for density in area A[7]:
    $$\tilde{\rho} = \frac{1}{|A|} \int_A \rho_{xy} \, \mathrm{d}x \, \mathrm{d}y \quad \text{with } \rho_{xy} \text{ Voronoi PDF or kernel density at point } (x, y)$$
  - Mean speed is the mean of pedestrians speed weighted by ρ_{xy}
  - Flow results from thermodynamic equation



(a) Density profile



(b) Velocity profile



(c) Specific flow profile

[7] Remain precise even if $|A|$ tends to 0, see B. Steffen and A. Seyfried. Phys A 389(9):1902 (2010)

Discrete versus continuous estimation for the density

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Main features

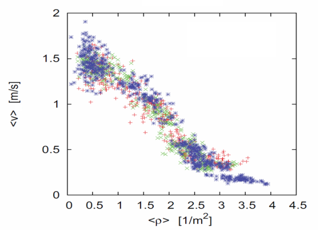
- Many characteristics and self-organizations of pedestrian dynamics have been established in the literature[8]
- They concern unidirectional or bidirectional streams (collective phenomena) as well as pedestrian individual behavior

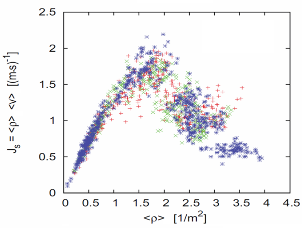
[8] See for instance D. Helbing. Rev Mod Phys 73:1067 (2001)

Fundamental diagram (FD)

- Describes the relation of flow (or mean speed) and density[9]
- Triangular shape for unidirectional flows: Free and congested states

  → Also been observed for cars or bikes[10] and explained by the reaction time: Free spacing distance proportional to the speed to avoid collision





[9] See A. Seyfried et al. J Stat Mech P10002 (2005)

[10] See J. Zhang et al. Phys Lett A 378(44):3274 (2014) for a comparison

FD: Speed decreases if density increases[11]

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[11] See A. Seyfried et al. J Stat Mech P10002 (2005)

FD: Influence of culture and motivation[12]

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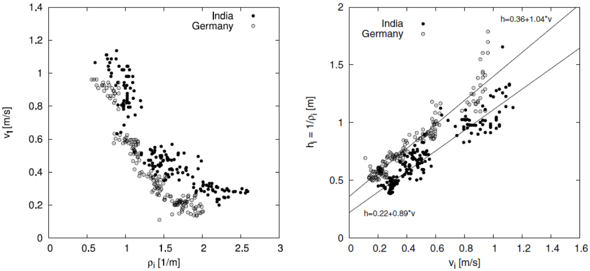
[12] U. Chattaraj et al. Adv Complex Syst 12(3):393 (2009)

FD: Influence of culture and motivation[13]



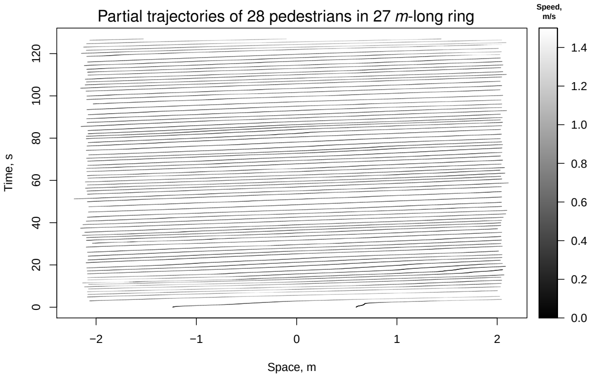
[13] U. Chattaraj et al. Adv Complex Syst 12(3):393 (2009)

Stop-and-go waves

- Phenomena occurring in unidirectional streams with high density levels[14] (congested states)
- Waves of stopped traffic propagating upstream
  $\rightarrow$ Alternation of congested and free states instead of (expected) homogeneous streams
- Self-organized phenomenon resulting from collective following behaviors[15]
  $\rightarrow$ Also frequently observed with cars in 1D lines[16]

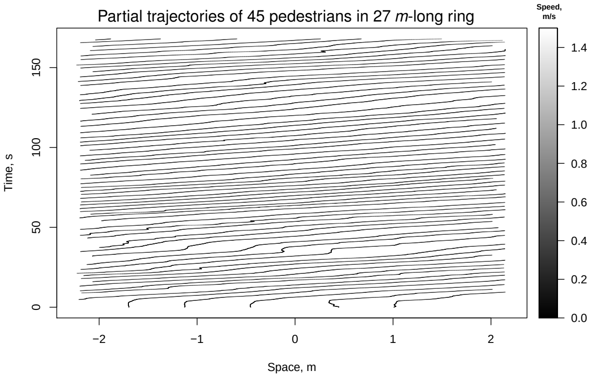
[14] A. Seyfried et al. In *Cellular Automata* 9th International Conference ACRI pages 496–505 (2010)
[15] The phenomenon is well described by models including a reaction time parameter
[16] See for instance Y. Sugiyama et al. New J Phys 10, 033001 (2008)

Stop-and-go waves[17]



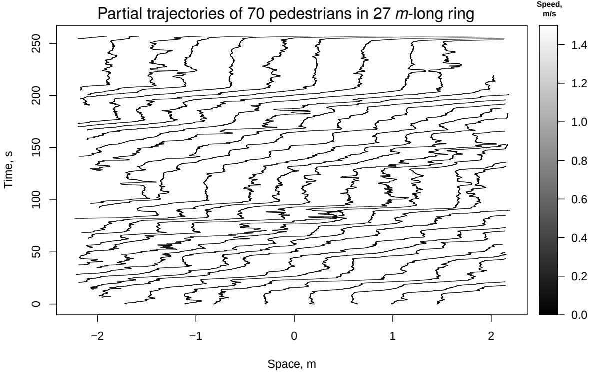
[17] A. Seyfried et al. In *Cellular Automata* 9th International Conference ACRI pages 496–505 (2010)

Stop-and-go waves[18]



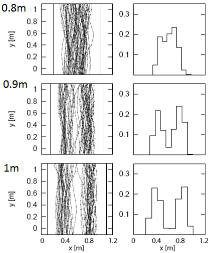
[18] A. Seyfried et al. In *Cellular Automata* 9th International Conference ACRI pages 496–505 (2010)

Stop-and-go waves[19]



[19] A. Seyfried et al. In *Cellular Automata* 9th International Conference ACRI pages 496–505 (2010)

Lane formation



- Unidirectional streams: Progressive formation of lanes (zipper effect)
  - $\rightarrow$ Flow linearly increases with corridor width[20]

- Bidirectional streams: Formation of lanes by direction (following of pedestrians with same direction)

[20] A. Seyfried et al. Transport Sci 43(3):395 (2009)

Lane formation by direction[21]

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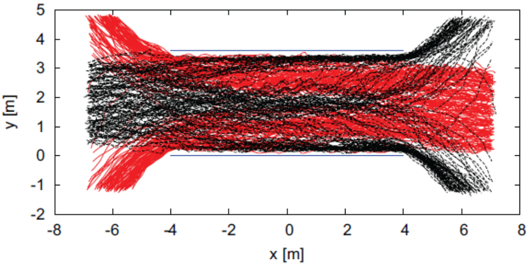
[21] See J. Zhang et al. J. Stat Mech Theor Exp 2012(02):P02002 (2012)

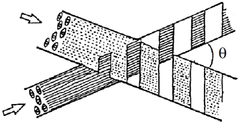
Lane formation by direction[22]



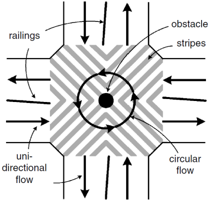
[22] See J. Zhang et al. J. Stat Mech Theor Exp 2012(02):P02002 (2012)

Stripe and circular flow at intersections

- Formation of **diagonal stripes** in intersection of two unidirectional streams[23]



- (Expected) formation of **circular flows** within intersecting streams with a pillar[24]



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[23] K. Ando et al. Railway Res Rev, 45:8 (1988)
[24] See D. Helbing et al. Transport Sci 39(1):1 (2005)

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Stripe formation

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Circular flow with a pillar

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Other features

- Clogging effect at bottleneck (social or granular[25])
- Similitude between bottleneck, corner and T-junction (linear increases of the flow with the widths[26])
- Oscillation by direction at bottlenecks[27] (bidirectional streams)
- Herding, group structures, oscillatory walker. . .[28]

[25] D. R. Parisi and C. O. Dorso. Phys A 354:606 (2005)
[26] J. Zhang and A. Seyfried. Transport Res Procedia 2:51 (2014)
[27] D. Helbing et al. Phys Rev Lett 97:168001 (2006)
[28] See for instance A. Schadschneider et al. *Extreme Environmental Events* Springer pages 517–550 (2011)

Crowd disaster

- Pedestrian crowd dynamics can also lead to tragic incidences when density level is very high and pedestrians are in contact[29]
- Pedestrian behaviors are not "social" regulations of spacings but with frictions
  - → The dynamics become close to turbulent ones of granular flow with shock waves and uncontrollable pushing
- The pressure level can be so high that metallic barriers are folded while it can be impossible for someone who falls to stand up

[29] Crowd disaster led to approximately 4 000 fatalities and 40 000 serious injuries during the past 100 years, see D. Helbing et al. Transport Sci 39(1):1 (2005)

Pedestrian models

- Three main scales of application[30]
  - The **strategic level** (highest spatial or temporal scale) for the modeling of route choice in complex buildings or urban context or the modeling of the choice of departure times
  - The **technical level** relates the choice of paths or exits in complex rooms where several paths or exits are possible
  - The **operational level** describes the interaction of pedestrians according to their neighborhood and the infrastructure

[30] See for instance S. P. Hoogendoorn et al. In *Pedestrian and Evacuation Dynamics* pages 123–155 (2002)

Modeling approaches

- Exist three main model classes for pedestrian dynamics[31]
  - **Macroscopic models** extracted from fluid dynamics theory (Eulerian coord.)
    Describe through PDE the evolution of density ρ, mean speed or flow Q
    Based on the continuity equation $\partial\rho/\partial t + \partial\rho/\partial x = 0$
  - **Mesoscopic models** extracted from the thermodynamics theory (Eulerian coord.)
    PDE for the dynamics of the probability density of the pedestrians as a function of the time, position and speed
  - **Microscopic models** where the pedestrians are seen as autonomous entities in interaction (Lagrangian representation)
    Self-driven or self-propelled many-particle systems

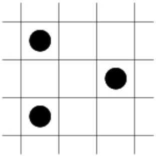
[31] See for instance D. Helbing. Rev Mod Phys 73:1067 (2001)

Microscopic models specificities

- Main characteristics of microscopic modeling approaches[32]
  - Time and space parameters and the state variables, that can be discrete or continuous
  - Determinist or stochastic models
  - Force-based approaches with extrinsic feeling of forces (Newtonian mechanics) vs Rule-based models with intrinsic decision process of an agent (psychology)
  - High vs Low fidelity: Many mechanisms and parameter vs minimalist models

[32] A. Schadschneider et al. *Stochastic Transport in Complex Systems. From Molecules to Vehicles*. Elsevier (2010)

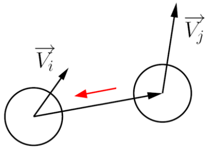
Cellular automaton



- Discrete time, space and state variables
- System is composed by cells that can either be free or occupied by a pedestrians
- Pedestrians synchronously jump from one cell to the next one according to space and time invariant rules based on the states of the neighbor cells[33]
  - Size of a cell = Size of a pedestrian
  - Exclusion rules between the pedestrians

[33] See for instance C. Burstedde et al. Phys A 295:507 (2001)

Force-based models



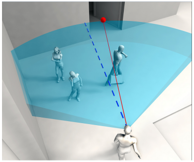
- Continuous in time and space
- Generally defined by systems of second order differential equation (acceleration functions)[34]

$$m\ddot{\mathbf{x}}_n = \underbrace{\frac{m}{T}(\mathbf{v}^d - \dot{\mathbf{x}}_n)}_{\text{Attraction to the desired speed}} + \underbrace{\sum_{m \neq n} \mathbf{F}_{n,m}^{rep}}_{\text{Repulsion with the neighbors}}$$

with $\mathbf{x}_n$ the position of pedestrian n with mass m and desired speed $\mathbf{v}^d$

[34] See for instance M. Chraibi et al. Phys Rev E 82:046111 (2010)

Speed models



- Non-inertial first order models (speed functions)[35]
  - **Vision-based** models based on time-to-collision variables calculated by predicting the movements of the neighbors[36]
  - **Velocity-obstacle** models used in robotic[37]
  - **Multi-agents** models describing pedestrian dynamics with a high fidelity

[35] F. Dietrich and G. Kster. Phys Rev E 89:062801 (2014)
[36] M. Moussaid et al. PLoS Comput Biol 8(3):e1002442 (2012)
[37] P. Fiorini and Z. Shiller. The International Journal of Robotics Research 17(7):760 (1998)

Calibration and validation

- Models depends on parameters that have to be calibrated and validated with (real or experimental) data
- *Bottom-up* approach:
  - Estimation of (microscopic) parameters with microscopic performances (i.e. trajectories)

  $\rightarrow$ Estimations by least square (descriptive method), maximum likelihood or by using Bayesian methods (parametric methods)[38]

  - Validation of the models by observing (by simulation) the macroscopic performances

  $\rightarrow$ Simultaneous control of local and global dynamics within bottom-up approach[39]

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[38] S. P. Hoogendoorn et al. In *Pedestrian and Evacuation Dynamics* page 329–340 (2007)

[39] by opposition to *top-down* approach where the models are calibrated in order to reproduce macroscopic performances (microscopic behaviors unknown)

Analysis of the models

- The microscopic models are generally described by simulation
  - CA models, defined in discrete time, can be directly simulated
  - Numerical resolution for force or speed based models by differential equation systems

  → In general, Euler explicit schemes are used
- Models only described analytically in particular simple cases
  - Linear stability analysis of the uniform solution on 2D infinite plans or spheres[40]

  → Solving of polynomial or polynomial-exponential characteristic equations
  - 1D stochastic models described in stationary states by solving master equation[41]

  → Approximation (or exact result) by mean-field with product form for pedestrian distribution

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[40] See for instance A. Nakayama et al. Comput Phys Commun 177:162 (2007)

[41] See A. Schadschneider et al. *Stochastic Transport in Complex Systems. From Molecules to Vehicles*. Elsevier (2010)

Routing models

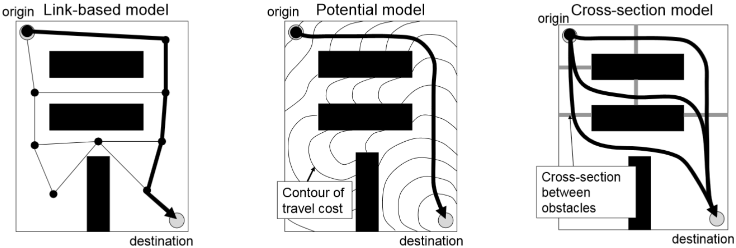
- Routing models describe dynamic decision process of pedestrians when several exits or paths are available
- Most of the approaches consists in utility maximization
  - $\rightarrow$ Optimization of travel time or travel distance[42]
- Another challenge is how to reach a selected target
  - $\rightarrow$ Active walker model for free situations[43] or queuing models for congested scenarios[44]

[42] See for instance A. U. Kemloh Wagoum and al. Adv Complex Syst 15(3):1250029 (2012) or G. Lämmel et al. Transport Res C–Emer 18(1):84 (2010)

[43] D. Helbing et al. Nature 388:47 (1997)

[44] M. Chraibi et al. In *Traffic and Granular Flow 11* pages 263-275 (2013)

Routing models: Illustration[45]



[45] M. Asano et al. Transport Res Rec 2039:42 (2007)

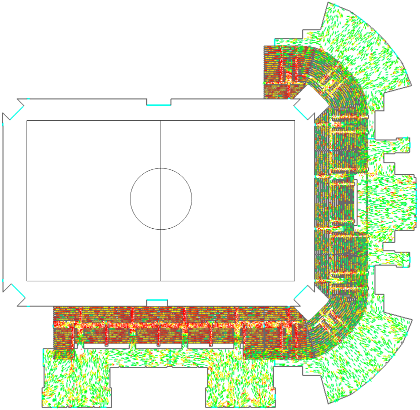
Simulation in complex environments

- Complex environments: Train stations, airports, shopping malls, stadiums or trade fair centers. . .
- Exist many simulation tools for academic and commercial use incorporating all the modeling levels
  - → For instance Exodus, Pedgo, Aseri, Simulex, FDS-Evac, JuPedsim[46]
- Many real applications have been investigated in the literature (stadiums, bridges or even larger scenarios like city-wide evacuations)
  - → Runtime can become an issue for large scenarios
  - → Use of optimization techniques such as multicore architectures indispensable[47]

[46] See C. Rogsch and W. Klingsch. vfdb International Fire Protection Symposium (2010) and `github.com/JuPedSim`

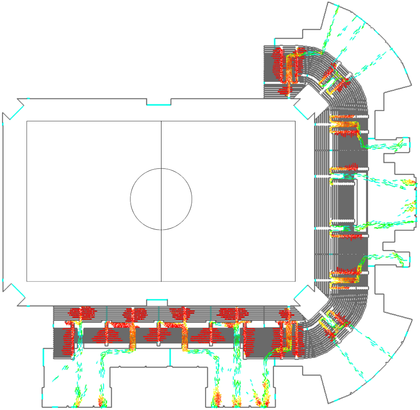
[47] A. U. Kemloh Wagoum. *Schriften des Forschungszentrums Jülich* 17 (2013)

Example: Stadium evacuation using JuPedSim[48]



[48] github.com/JuPedSim

Example: Stadium evacuation using JuPedSim[49]



[49] github.com/JuPedSim

Conclusion

- Analysis of pedestrian dynamics lead to many fields of research between applied mathematics and statistic, physics and computer science
  - **Video content analysis to track the pedestrians and obtain real trajectories**
  - **Identification of self-organized phenomena (complex system)**
  - **Development and statistical calibration of models**
  - **Analysis of the models by simulation or, in basic cases, with mathematical tools for dynamical systems**

Thank you for your attention!

Ju falenderoj për vëmendjen tuaj!

// Free access online //

*	Trajectories collection with PeTrack :	ped.fz-juelich.de/petrack/
*	Database of various experiments :	ped.fz-juelich.de/database www.asim.uni-wuppertal.de/datenbank
*	Simulation module JuPedSim :	github.com/JuPedSim